AMPLITUDE CORRECTIONS FOR REGIONAL SEISMIC DISCRIMINANTS

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ABSTRACT

We present an update on seismic event identification methodologies being investigated as part of the Department of Energy CTBT R&D program. A fundamental problem associated with event identification lies in deriving corrections that remove source and path effects on regional phase amplitudes used to construct discriminants. Our goal is to derive a set of physically based corrections that are independent of magnitude and distance, and amenable to multivariate discrimination by extending the technique described in Taylor and Hartse (1998). For a given station and source region, a number of well-recorded earthquakes are used to estimate source and path corrections. The source model assumes a simple Brune (1970) earthquake-source that has been extended to handle non-constant stress drop. The propagation model consists of a frequency-independent geometrical spreading and frequency-dependent power-law Q. A grid search is performed simultaneously at each station for all recorded regional phases over stress-drop, geometrical spreading, and frequency-dependent Q to find a suite of good-fitting models that remove the dependence on m_b and distance. Seismic moments can either be inverted for or fixed and are tied to m_b through two additional coefficients. Once a set of corrections is derived, effects of source scaling and distance as a function of frequency are applied to amplitudes from new events prior to forming discrimination ratios. Thus, all the corrections are tied to just m_b and distance and can be applied very rapidly in an operational setting. Moreover, phase amplitude residuals as a function of frequency can be spatially interpolated (e.g. using kriging) and used to construct a correction surface for each phase and frequency. The spatial corrections from the correction surfaces can then be applied to the corrected amplitudes based only on the event location.

Key Words: seismic, discrimination, identification, nuclear

OBJECTIVE

The objective of this work is to outline a methodology for correction of regional amplitudes used to construct discriminants for earthquake source and path effects using simple physical models. The methodology produces discriminants that are multivariate normal and can be rapidly applied in an operational setting.

RESEARCH ACCOMPLISHED

We have outlined a procedure for simultaneously correcting for both propagation and source effects to seismic amplitudes prior to forming amplitude ratios. Correcting amplitudes offers several advantages over correcting ratios. First, correcting amplitudes using simple physical models offers much flexibility in that all information is retained as opposed to partial censoring of data by pre-selecting ratios. Also, because of hidden correlation structures of different ratios, it is difficult to *a priori* select a set of discriminants that will give optimum performance. The best discrimination performance is not necessarily achieved by pre-selecting the best amplitude ratios. In fact, combining a discriminant that by itself does not work well with one that does, may lead to improved overall performance (e.g. Taylor and Hartse, 1997). The problem is exacerbated if little or no explosion calibration information is available, which is the case for most stations that will be used in monitoring the CTBT. Additionally, preselected ratios may be highly interdependent leading to a false impression of discrimination capability. It has been observed that seismic discriminants can show significant regional variability that is a function of factors such as crustal velocity structure and explosion-source material properties. Thus, in areas where little or no calibration information from explosions is available, it may not be prudent to pre-select ratios.

We illustrate that the amplitude-correction parameters can be based on simple physical models which can be difficult to do with ratios because of tradeoffs between different parameters. Thus, in uncalibrated or poorly calibrated regions, reasonable corrections can be obtained using expert opinion or extrapolation from geophysically similar regions. Further, we will show that for a given station and source region, the residuals from the one-dimensional model can be spatially interpolated for each phase and frequency band (e.g. using kriging) to account for lateral variations in propagation. It has been shown that geographical interpolation can be used to create correction surfaces that significantly reduce scatter in discriminants. The corrections appear to be particularly effective at low (1 Hz) frequencies (e.g. Taylor and Hartse, 1998, Phillips *et al.*, 1998).

We have developed a methodology for removing m_b and distance trends from regional seismic amplitudes (MDAC – Magnitude and Distance Amplitude Corrections). MDAC is an improved version of the SPAC (Source and Path Amplitude Corrections) discussed by Taylor and Hartse (1998) and Taylor and Velasco (1998). Improvements over SPAC include the inclusion of a grid search over trial values of stress drop, geometrical spreading, and attenuation parameters. We have also established a tie between m_b and $\log M_0$ using the earthquake source model (rather than a linear relationship as assumed in Taylor and Hartse, 1998).

The MDAC method combined with spatial interpolation of amplitudes (e.g. kriging) represents a station-specific approach for computing discriminants that are multivariate normal for a given source region. For a given station and source region, six MDAC parameters (Q_0, η, γ, σ_b, F_{mb}, A_{mb}) are derived for each regional phase. The first three terms are the Q values at 1 Hz (Q_0), the geometric spreading coefficient (η) and the power law coefficient (γ) for frequency-dependent attenuation and control the path corrections. The fourth term is the Brune stress drop (σ_b). The last two terms (F_{mb}, A_{mb}) control the scaling between the seismic moment and magnitude (m_b) and control the source scaling. The MDAC-corrected amplitudes can be spatially interpolated using kriging (e.g. Schultz *et al.*, 1998) to derive a correction surface for each phase as a function of frequency. These surfaces can be used to reduce scatter in the corrected amplitudes and improve discrimination performance. The MDAC parameters and kriged surfaces can be developed offline and entered into an online database for rapid pipeline processing. Once a new event is located and a m_b is calculated, the regional phases can be windowed and Fourier transformed. The MDAC-corrected amplitudes for each phase and frequency can be computed using only the distance and m_b. The spatial corrections from the kriged surfaces can then be applied to the corrected amplitudes based only on the event location. At this point, a set of multivariate-normal corrected amplitudes is available for event identification.

Estimation of Source and Path Parameters Using MDAC

In this section we briefly describe the method we use for inverting for source and path parameters and forming a set of frequency-dependent amplitude corrections for each phase recorded at a given station. In our formulation, we follow a modification of the techniques of Sereno *et al.*, (1988), Taylor and Hartse (1998) and Taylor and Velasco (1998).

At a particular station and source region, we assume the instrument-corrected amplitude spectrum for a given phase, $A_i(f)$, for source i, is given by

$$\log A_i(f) = \log G(r_i, r_0) + \log S_o^{(i)} - \log\left[1 + \left(\frac{f\left(S_o^{(i)}\right)^{\kappa}}{c}\right)^2\right] - \frac{\pi \log e}{Q_0 v} f^{1-\gamma} r_i + \log P(f) \qquad (1)$$

where the first term on the right controls the geometrical spreading, the second two terms the source scaling, the fourth term the frequency-dependent attenuation, and the last term is a phase site/excitation factor (for details, see Taylor *et al.*, 1999). We perform a combination grid search and inversion to determine the main MDAC parameters given above.

Application of MDAC to Western China Data Recorded at MAKZ

As an illustration of the MDAC methodology, we present results from the IRIS GSN station MAKZ (Makanchi, Kazakhstan). All seismograms were obtained from the IRIS Data Management Center (DMC). The data are from 4 Lop Nor nuclear explosions and 412 earthquakes located in a region around Lop Nor extending between 35° and 50° N latitude and 80° and 100° E longitude (the Lop Nor box; Figure 1). As discussed by Hartse *et al.*, (1997), we measured RMS amplitudes taken in 8 different 1 octave frequency bands ranging from 0.5 to 8 Hz. Because the methodology discussed above is for a spectral inversion, we convert the RMS amplitudes to pseudo-spectral amplitudes using Parseval's Theorem for the discrete Fourier. We first computed 6 MDAC parameters including moment for the Lg amplitudes. A grid search was performed for each phase for six logarithmically spaced stress drops between 0.1 and 30 MPa, 50 points each for η, Q_0, and γ, between 0.5 and 1, 300 and 800, and 0 to 1, respectively resulting in 750,000 combinations of parameters.

The next step involves examining the best-fit solutions to see if they adequately remove trends with m_b and distance. To do this we select a specified number of the best-fit solutions and regress the corrected amplitudes versus both m_b and linear distance. At this stage, we go though and recorrect the amplitudes based on the m_b – $\log M_0$ scaling relationship.

Figure 2 shows an example of Lg parameters and fits to our selected model. Because we used Lg to invert for $\log M_0$, the site/excitation factors are small (upper left portion of Figure 2). The numerous tradeoffs between the different parameters make it not difficult to get a good fit to the observed spectrum as seen by the upper right portion of Figure 2.

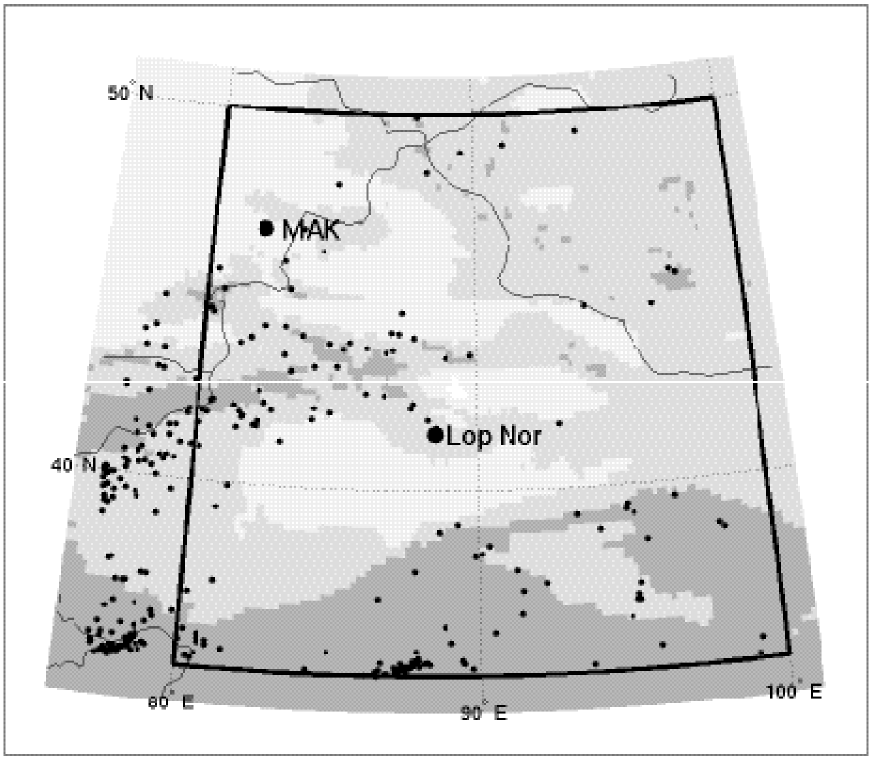

Figure 1. Map showing events used in this study within box surrounding Lop Nor.

We then corrected all amplitudes that passed the signal-to-noise cutoff of 1 using pre-phase noise including the 4 Lop Nor nuclear explosions. Figure 3 shows the corrected log amplitudes for each phase as a function of frequency for all four phases. We have also identified four earthquakes occurring within 50 km of the Lop Nor test site.

As expected, the corrected amplitudes for the earthquakes are very close to zero mean, and χ^2 goodness-of-fit tests show most frequency bands are normally distributed. The explosions show a significantly different pattern than the earthquakes. This is not unexpected, since we are using an earthquake model to fit the data. The misfit is particularly severe for Pn as can be seen by the high residuals at intermediate and high frequencies. As will be further illustrated below, the plot in Figure 3 is interesting in that it can be used as a guide in selecting individual discriminants that provide good separation between earthquakes and explosions. For example, it can be seen that a high frequency Pn to low-frequency Sn or Lg cross spectral ratio will give excellent separation between the earthquakes and explosions (as noted by Hartse *et al.*, 1997). Additionally, a Pn, Pg, or possibly even an Sn spectral ratio will provide good separation. These observations reinforce our earlier comments about the potential restrictions on discrimination performance by *a priori* selecting ratios.

At this point we can directly make traditional discrimination plots from the corrected amplitudes shown in Figure 3 by simply taking differences (log ratios) using any combination of phase and frequency. This is illustrated in Figure 4 where we show the high-frequency (4-8 Hz) Pn to low-frequency (0.75-1.5 Hz) cross-spectral ratio plotted versus both distance and magnitude.

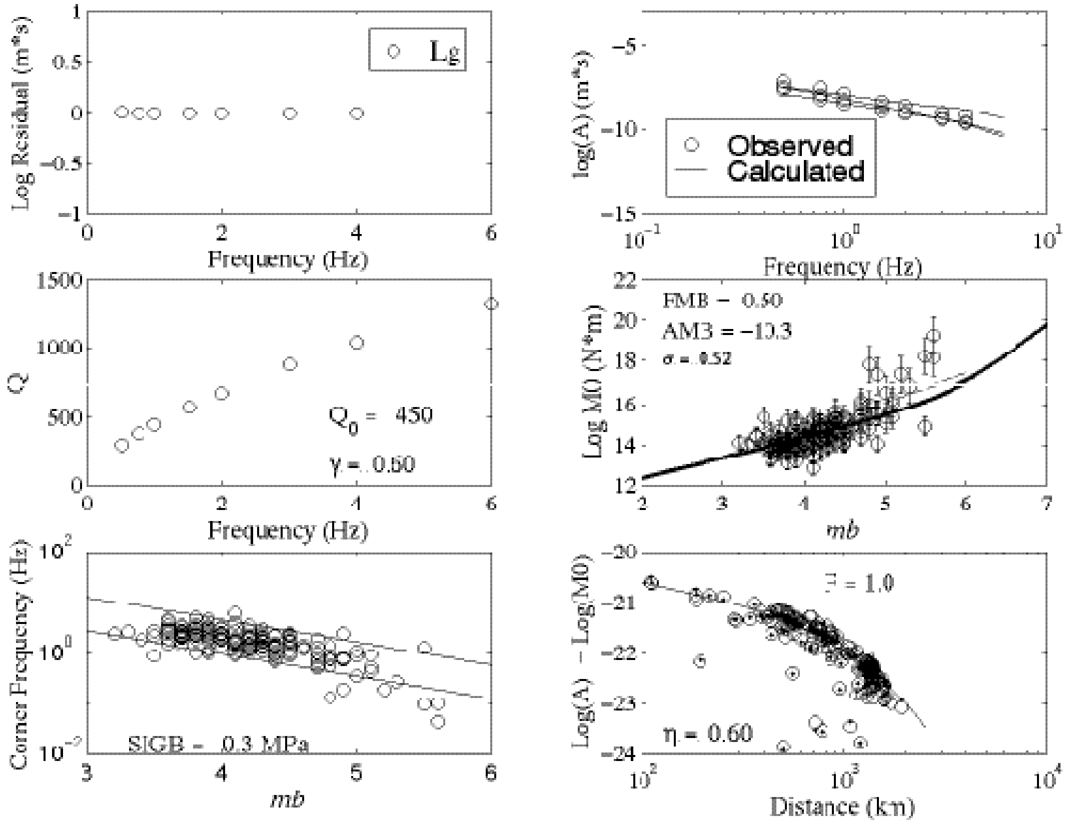

Figure 2. Plots illustrating various parameters for Lg MDAC model. Moving clockwise from upper left (UL): Site/excitation factors (equation 1, *P(f)*). (Upper right) Example of three fits to three randomly chosen events. (Middle right) Moment/magnitude relationship and estimated moments and 95% confidence limits. Dashed line is from universal moment-magnitude scaling (Priestley and Patton, 1997). (Bottom right) Observed (open circle) and calculated (dot) amplitude normalized by moment versus distance at 1 Hz versus distance and theoretical scaling for $\eta = 0.6$. (Lower left) Estimated corner frequency versus m_b for average stress drop of 0.3 MPa. Upper and lower lines are theoretical curves for 0.1 and 10 MPa (1 and 100 bar) stress drop. (Middle left) Q versus frequency using power law model.

From Figure 4 it can be seen that the trends in the ratio are removed with both distance and magnitude. The separation between the earthquakes and explosions is quite good (including the Lop Nor earthquakes). Further examples of various discrimination ratios computed from the MDAC-corrected amplitudes are shown in Figure 5. Note that in all cases the discrimination performance is excellent and trends are removed with magnitude. The separation between the Lop Nor explosions and earthquakes is very good indicating that the discriminants are based on source or very near-source differences between the two different source types.

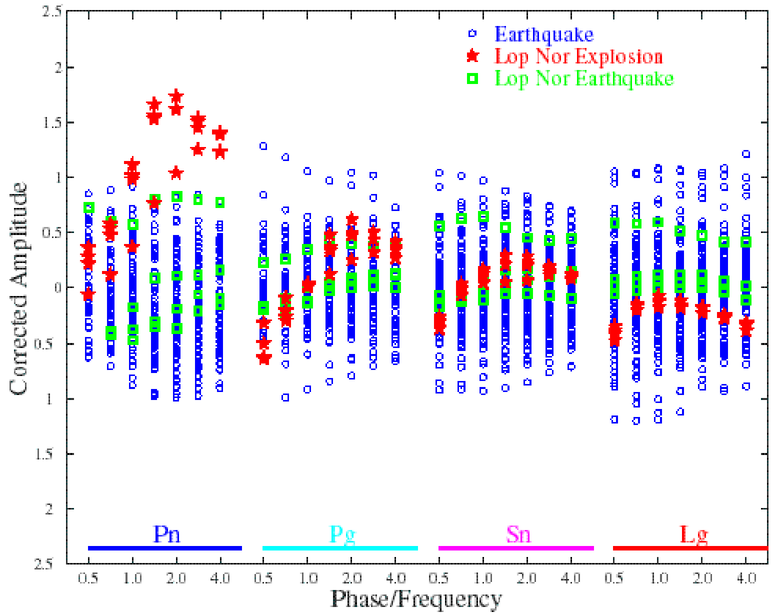

Figure 3. MDAC-corrected log amplitudes for each phase as a function of frequency using the parameters shown in Figure 2 including the 4 Lop Nor nuclear explosions. Four earthquakes within 50 km of Lop Nor are also identified.

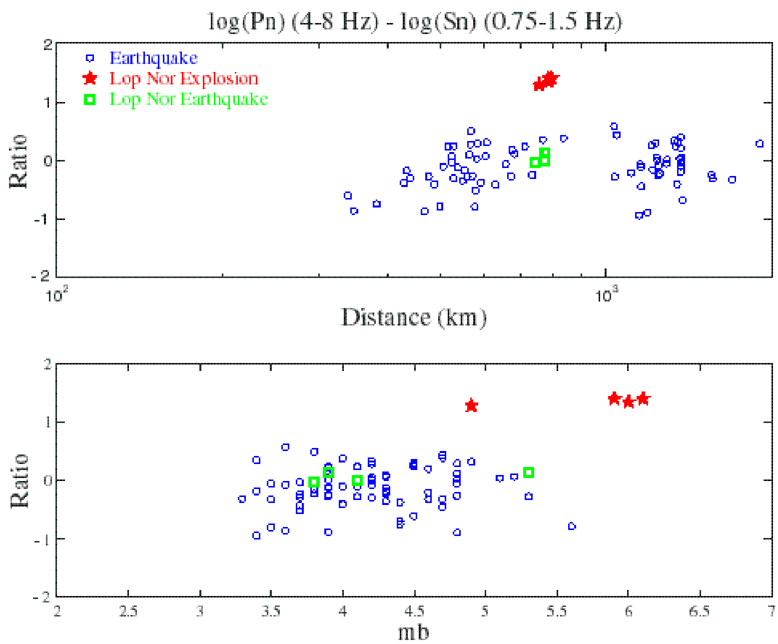

Figure 4. High-frequency Pn (4-8 Hz) to low-frequency (0.75-1.5 Hz) Sn cross-spectral ratio plotted versus log distance (top) and magnitude (bottom).

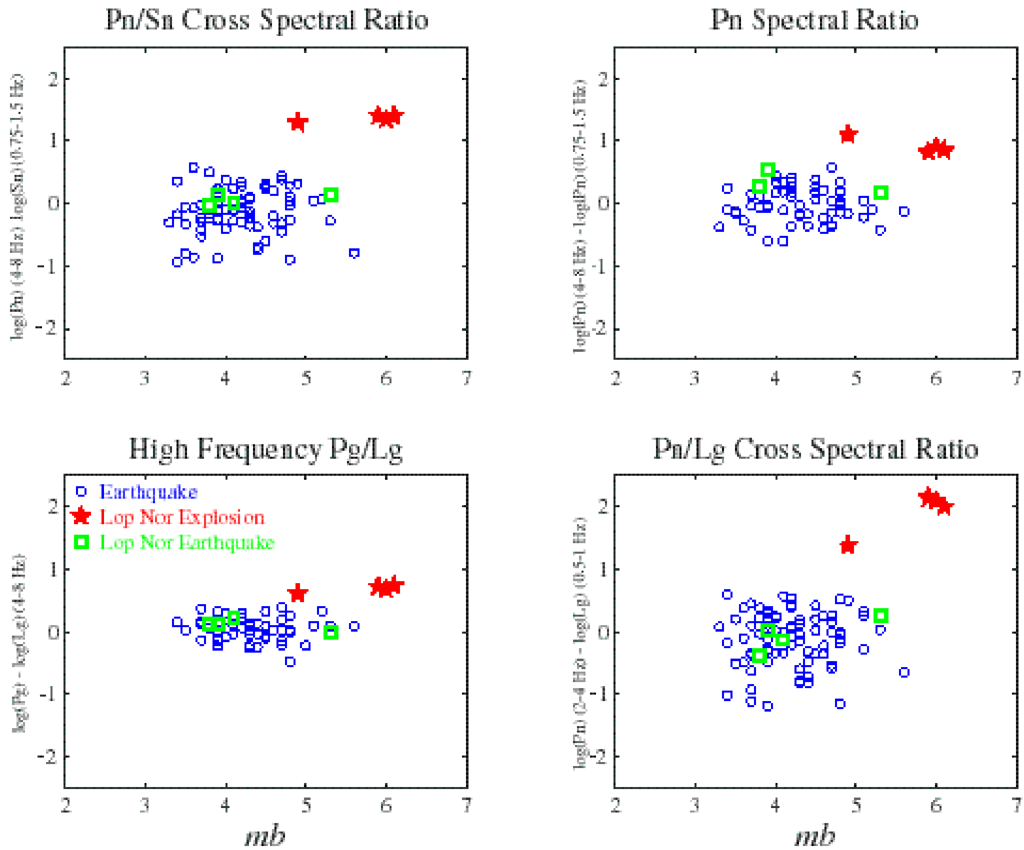

Figure 5. Examples of four discriminants computed from the MDAC-corrected amplitudes shown in Figure 3. Upper left is the Pn/Sn cross-spectral ratio (shown in Figure 4). Upper right is a Pn spectral ratio. Lower right is a Pn/Lg cross-spectral which from Figure 3 was judged to have the most separation between earthquakes and explosions. Lower left, high-frequency Pg/Lg ratio.

The discriminants in Figure 5 illustrate that one-dimensional models for a given station and source-region can lead to good discrimination performance. However, as suggested by Taylor and Hartse (1998) and Phillips *et al.*, (1998), the residuals to the one-dimensional model can be spatially interpolated to account for regional variations in attenuation further reducing the scatter in the discrimination plots. Phillips (1999) and Rodgers *et al.*, (1999) have suggested kriging (e.g. Schultz *et al.*, 1998) as a viable method to spatially interpolate amplitudes.

Using leave-one-out, we corrected the amplitudes and recomputed the Pn to Sn cross-spectral ratio shown in Figure 4. The results are shown in Figure 6 along with the original MDAC-corrected spectral ratio with just a simple distance correction (Hartse *et al.*, 1997). In each plot, we show the estimate of the variance of the earthquake population and an estimate of the univariate Mahalanobis distance between the earthquake and explosion populations, Δ^2 (Hand, 1981). For the lower two plots we show the variance reduction relative to the preceding plot. For the DCR shown in the top portion of Figure 6, we can still see the source scaling effect on the cross-spectral ratio.

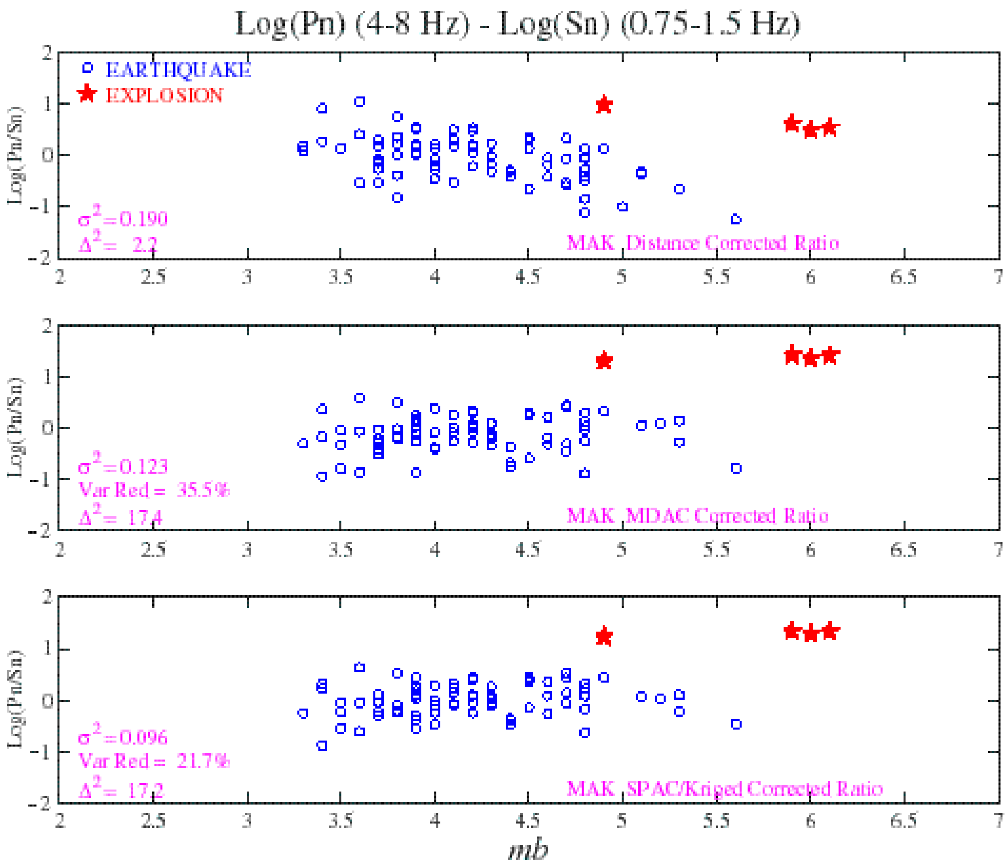

Figure 6. Examples of high-frequency Pn to low-frequency Sn cross spectral ratio versus magnitude with estimated variance for earthquakes and Mahalanobis distance. (top) Distance corrected. (middle) MDAC-corrected ratio (bottom) Results from application of kriged surface corrections to individual MDAC-corrected amplitudes and recomputation of ratio.

The middle plot on Figure 6 shows the MDAC-corrected ratio (same as Figure 4) showing a variance reduction over the DCR of 35.5%. The Δ^2 value has also increased significantly because of the removal of the ratio versus magnitude trend resulting in better discrimination performance. The bottom portion of Figure 6 shows results from application of kriged surface corrections to individual MDAC-corrected amplitudes and subsequent recomputation of the ratio. The variance has been reduced an additional 21.7% over the MDAC ratio (49.5% over the DCR). Although the variance of the earthquakes has been reduced significantly, the Mahalanobis distance has not changed significantly because the correction has moved the two populations slightly closer together due to the nature of the corrections in the vicinity of Lop Nor. Thus, although the one-dimensional models can be used to correct discriminants and obtain good performance, the spatial surface corrections can be used to improve discriminants even further by reducing the scatter in the earthquake population.

The MDAC methodology presented in this paper can be easily incorporated into an operational pipeline. The concept is illustrated in Figure 7. The MDAC parameters and kriged surfaces can be developed offline and entered into an online database for pipeline processing. Once a new event is located and a m_b is calculated, the regional phases can be windowed and Fourier transformed. The MDAC-corrected amplitudes for each phase and frequency can be rapidly computed using only the distance and m_b. The spatial corrections from the kriged surfaces can then be applied to the corrected amplitudes based only on the event location. At this point, a set of multivariate-normal corrected amplitudes is available for event identification.

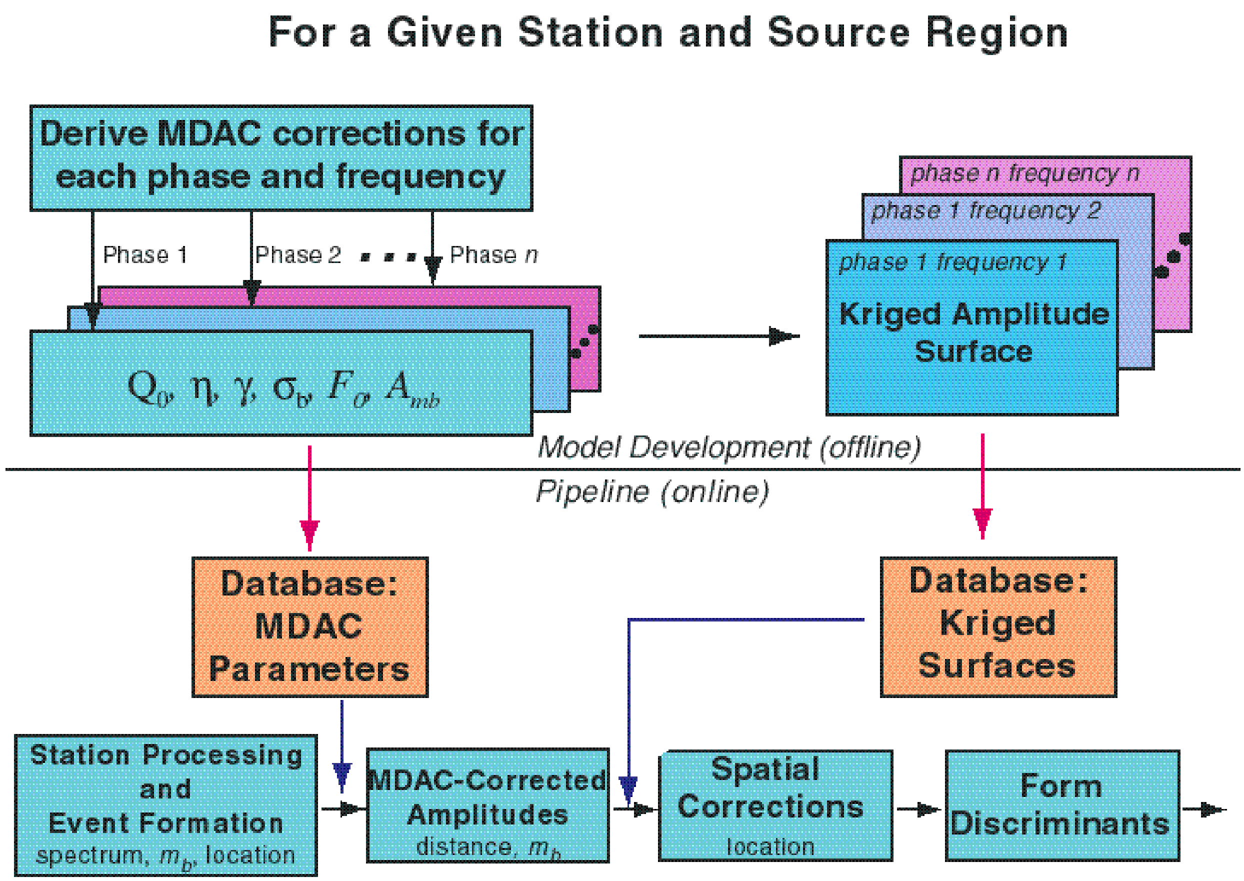

Figure 7. Example flowchart illustrating how the MDAC method could be combined with spatial interpolation (e.g. kriging) to develop database parameters to provide amplitude corrections for regional event identification in near-real time. These parameters can easily be incorporated into an operational pipeline to correct amplitudes from a new event for identification purposes.

CONCLUSIONS AND RECOMMENDATIONS

We have presented the MDAC methodology for correcting regional seismic amplitudes for source scaling and propagation using simple physical source and propagation models. The resulting corrected amplitudes are independent of m_b and distance and amenable to multivariate discrimination analysis. The amplitudes are corrected using a simple one-dimensional propagation model and the Brune (1970) dislocation source model modified to handle non-constant stress drop. The discrimination power in the corrected amplitudes lies in the assumption that the earthquake model will provide a poor fit to the signals from an explosion. Observations of explosions from many different regions have shown significant variability in performance of different discriminants presumably due to the strong effect of linear and nonlinear material-dependent phenomenology acting in the near-source region (e.g. Taylor and Denny, 1991). However, it is expected that there will always be some, possibly unpredictable, differences between earthquake and explosion sources. This fact is the basis for our preference for deriving a set of corrections for seismic amplitudes rather than preselecting traditional amplitude ratios. In an uncalibrated region, it is very difficult to predict *a priori* which combination of discriminants will provide the best performance. Correcting amplitudes allows for much flexibility in the subsequent event identification procedures (Figure 7) because all of the information is retained. Dealing with amplitudes involves a new set of problems (e.g. the m_b bias problem) not encountered as strongly with ratios. However, we feel the advantages outweigh the disadvantages in terms of the flexibility amplitudes give to the source identification problem.

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